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HEAT INPUT CALCULATED FROM BORE SURFACE TEMPERATURES IN GUNS

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U. S. Naval Proving Ground
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Heat Input Calculated from Bore Surface Temperature in Guns

by

J. Nanigian
Armament Department

NPG REPORT NO. 1365

Foundational Research
Project NPG-M-11016-9

5 May 1955

APPROVED: J. F. BYRNE
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CONTENTS

ABSTRACT

Heat transfer curves calculated from bore surface temperature time curves are presented. Bore surface temperatures were recorded on the 3"/70 Type E Mod 0 Gun at the origin of rifling region and the 40mm Mark A Mod 1 Gun at 30"0 from the breech face. Typical "hot" and "cool" powders were used on the 3"/70 gun firings and typical solid and liquid propellants were used on the 40mm gun firings.

The results indicate that the total heat transferred to the 3"/70 barrel at the origin of rifling region is approximately proportional to the calculated flame temperatures of the two powders. Both powders were fired under similar firing conditions at service velocities. The total heat transferred to the 40mm barrel at 30"0 from the breech face for the liquid propellant rounds is about 80% of the total heat input transferred for the solid propellant rounds. However, in this instance, the firing conditions were not identical since the muzzle velocity for the solid propellant rounds was 2800 fps and only 2500 fps for the liquid propellant rounds.

FOREWORD

This is the fourth partial report on Foundational Research Project NPG-M-11016-9, "Investigation of Heat Input to Guns by Strain Gauge Methods and Bore Surface Temperature Measurements", and the twenty-fifth partial report under the Foundational Research Program of the Naval Proving Ground authorized by reference (a).

The firings on the 3"/70 Type E Mod 0 Gun reported in this test were conducted during October thru November 1953. The firings on the 40mm gun were conducted during September 1954. The computations were done during the period from December 1954 to January 1955 on the Aiken Relay Calculator located at the Naval Proving Ground.

The author wishes to acknowledge the assistance and cooperation of Messrs. J. H. Walker and M. Macchia in carrying out the work involving the use of the Aiken Relay Calculator. Also, the author is indebted to Mr. R. I. Rossbacher for his assistance with the mathematics involved in the heat transfer calculations.

This report was reviewed by:

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INTRODUCTION

Much time and effort have been spent on the problem of determining the heat transfer to a gun barrel during firing. The factors of gun erosion, thermal stresses, optimum firing rates and barrel coolants depend upon the heat transfer to the barrel. Until recently, the heat input to the barrel has been estimated by the following conventional methods: (1) external thermocouples applied to the barrel, (2) embedded thermocouples and (3) external strain gauges installed on the barrel to record the thermal strain.

Each of these methods has its disadvantages, and it has long been recognized that the ideal method for measuring the heat transfer to the barrel consisted of measuring the temperature history of the bore surface. The rigid requirements for such a thermocouple have prevented the recording of these measurements on large caliber guns until recently (references (b) and (c)).

With the advent of a thermocouple capable of recording the bore surface temperature histories of large caliber guns accurately and consistently, the problem of calculating the heat transfer and the rate of heat transfer has been simplified. Similar bore surface thermocouples have been recently constructed for use on small caliber guns by the Naval Proving Ground.

The object of this report is to present heat transfer data calculated from typical bore surface temperature measurements on the 3"/70 Type E Mod 0 and the 40mm Mark A Mod 1 Guns. Bore surface temperature measurements were taken on the 3"/70 gun at the origin of rifling, using both "hot" and "cool" powders. Bore surface temperatures were recorded on the 40mm gun at 30"0 from the breech face, using both solid and liquid propellants.

DESCRIPTION OF MATERIAL

3"/70 Type E Mod 0 Gun Powders:

Two different powders were used in these firings: SPDN-10114, a "hot" powder with a calculated flame temperature of 2481°K, and EX 6586, a "cool" powder with a calculated flame temperature of 2065°K. The chemical and physical characteristics of these powders are contained in Table 1. Both powders were fired under identical conditions using a 15.0 pound projectile at a muzzle velocity of approximately 3400 fps.

40mm Mark A Mod 1 Gun Propellants:

Both solid and liquid propellants were used in these firings. The solid propellant consisted of 305.3 gms of SPDN-8541 with a calculated flame temperature of 2380°K. The chemical and physical characteristics of this powder are contained in Table 2. The liquid propellant consisted of 180 gms of 67% hydrazine, 23% hydrazine nitrate and 10% water, with 5% free volume. Mark 2 projectiles, whose weights were adjusted to 902 gms, were fired with both types of propellants. The muzzle velocities on the solid and liquid propellant rounds were about 2800 fps and 2500 fps respectively. The maximum breech pressures on the solid and liquid propellant rounds were about 45,000 psi and 50,000 psi respectively. (Bore surface temperatures were taken on this gun incidental to other tests.)

DESCRIPTION OF TEST EQUIPMENT

3"/70 Type E Mod 0 Gun:

The bore surface thermocouple used on this gun is described in detail in references (b) and (c). Briefly, the thermocouple consists of a strip of nickel foil, approximately 1/8" wide and 0.0002 thick, which is sandwiched between the flat surfaces of a split steel cylinder. Two thin sheets of mica (3-6 microns thickness) are used for insulation between the two elements.

TABLE 1

CHEMICAL AND PHYSICAL CHARACTERISTICS OF POWDERS USED IN 3"/70 TYPE E MOD O GUN

Chemical Characteristics (Per Cent Composition)

Powder Index	Nitrocellulose	Dinitrotoluene	Diphenylamine	Centralite	Dibutylphthalate	Total Volatiles	Total Ash
SPDN-10114	82.33	11.35	.99	--	3.40	1.86	.07
		Nitroglycerin	Picrite				
EX 6586	20.33	8.90	60.74	2.09	7.94	.20	.04

Physical Characteristics

Powder Index	Diameter (D) (in.)	Diameter of Per. (d) (in.)	Web (in.) Inner	Web (in.) Outer	Web (in.) Avg.	Length (L) (in.)	Web Var.	L/D	D/d	Form	No. of Perf.	No. of Grs./lb.	S.G.	Calc. Flame Temp. °K	Nominal Flame Temp. °K
SPDN-10114	.254	.023	--	.049	.046	.606	--	2.4	11.0	Cyl.	7	637	1.6	2481	2500
EX 6586	.1425	.0132	.0248	.0266	.0257	.3500	7.0	2.45	10.8	Cyl.	7	3326	1.58	2065	2100

TABLE 2

CHEMICAL AND PHYSICAL CHARACTERISTICS OF SPDN-8541

Chemical Composition (Per Cent Composition)

Nitrocellulose	Diphenylamine	Dinitrotoluene	Dibutylphthalate	Potassium Sulfate	Alcohol	Water
81.33	1.08	10.41	5.21	.91	.58	.48

Physical Characteristics

Diameter	Diam. of Perf.	Average Web	Length of Grain	No. of Perf.	No. of grs./lb.	Ratio of Specific Heats	Calculated Flame Temp.	Impetus
.1195"	.0132"	.0200"	.2707"	7	6523	1.2609	2380°K	300,200 ft/lb./lb.

The two metals comprising the thermocouple may be made of any thermoelectric combination, although it is best to use for the split cylindrical sections the same material as the metal wall whose temperature is to be recorded. The assembly containing the split cylinder, mica and nickel foil is then threaded into an appropriate steel housing. Set screws and a press-fit ring are used to keep the unit together tightly. The end surface of the assembly is ground flat and polished perpendicular to the crack. A number of thermoelectric junctions are thus formed on the exposed surface.

40mm Mark A Mod 1 Gun:

The bore surface thermocouples used on this gun embodied a slight modification of the design described above. The two semicylindrical steel sections (comprising the steel element) were made in the form of a tapered wedge which was press-fitted into a steel housing containing an appropriate hole. The larger diameter of the wedge was exposed to the bore. This modification allowed for the construction of thermocouples to fit into a small hole drilled to the bore of the barrel. A total of 15 rounds were fired in the 40mm gun using this bore surface thermocouple with the thermal junction remaining in excellent condition throughout the test. The end surface of the thermocouple was recessed ".005 from the bore wall on these firings.

PROCEDURE

3"/70 Type E Mod 0 Gun:

The two representative bore surface temperature time curves chosen for analysis appeared in reference (c) as rounds 2 and 5 for the "hot" and "cool" powders respectively. The test procedure was outlined in that reference. Also, pressure curves and additional bore surface temperature curves using these two powders are contained in reference (c). The thermocouple was installed at the location 34 inches from the breech face which corresponds to the origin of rifling region on this barrel.

40mm Mark A Mod 1 Gun:

Firings were conducted using the 40mm Mark A Mod 1 gun barrel mounted in the 6-pounder mount Mark 7 Mod 1. The bore surface thermocouple was installed at the location 30"0 from the breech face. (The origin of rifling is 12"5 from the breech face.) The bore surface temperature curves for the solid and liquid propellants are typical for these propellants when firing in a "dry" barrel. When the barrel was lubricated prior to firing, the recorded bore temperatures were about 25% lower in magnitude and also had a slower rise time. Since the barrel is normally cleaned and greased at the end of each day's firing, the temperature records for the "warming" or first round of each day's firings were not used.

Heat Transfer Calculations:

It is assumed that the cylindrical divergence and the longitudinal flow of heat may be neglected during the firing of a single round. Also, it is assumed that the barrel may be represented by a semi-infinite medium. Since the bore surface temperature varies with time, it can be shown (reference (d)) that the temperature increment at any point in the medium is given by the equation:

$$\Delta T = \frac{x}{2\sqrt{\pi h}} \int_0^t \frac{\phi(\beta)}{(t-\beta)^{\frac{3}{2}}} e^{-\frac{x^2}{4h(t-\beta)}} \, d\beta \qquad (1)$$

where

β = time variable of integration

$\phi(\beta)$ = instantaneous bore surface temperature

x = distance from bore surface

h = thermal diffusivity

Since the heat input per unit area of the bore is given by $Q = \int_0^\infty C_p \rho \Delta T dx$, one finds by performing the integration over x, with the above expression for ΔT that:

$$Q(t) = \frac{k}{\sqrt{\pi h}} \int_0^t \frac{\phi(\beta)}{\sqrt{(t-\beta)}} d\beta \qquad (2)$$

with k the thermal conductivity. (It is assumed that the thermocouple is recording the temperature at the bore surface so that $\phi(\beta)$ is known.) The rate of heat transfer then is

$$q(t) = \frac{k}{\sqrt{\pi h}} \int_0^t \frac{d\phi(\beta)}{d\beta} \frac{d\beta}{\sqrt{(t-\beta)}} \qquad (3)$$

It must be remembered that the heat transfer calculations are taken as valid only up to the instant of projectile exit from the barrel.

The method of computing the actual values consisted of fitting parabolas to each set of three consecutive data points along the whole range of data points and then computing Q(t) and q(t) over each parabola. The intervals of time were adjusted so that no appreciable change in the calculated values resulted from any further subdivisions.

RESULTS AND DISCUSSION

3"/70 Type E Mod 0 Gun:

The bore surface temperature-time curves and the calculated heat transfer curves are contained in Figure 1. The total heat inputs at the instant of projectile exit are 31 cal./sq.cm. and 24 cal./sq.cm. for the "hot" and "cool" powders respectively. Thermal conductivity and

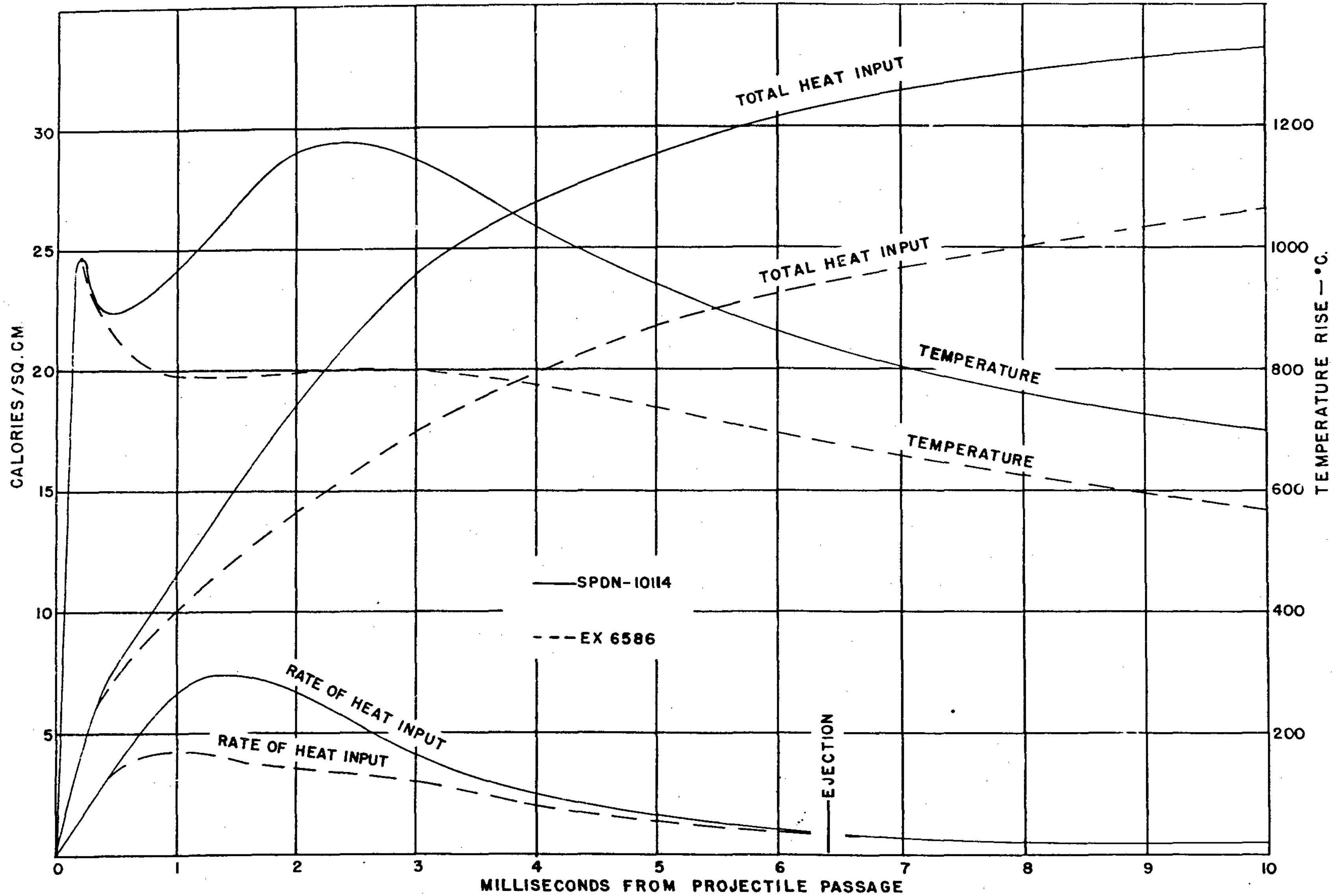

FIGURE I

BORE TEMPERATURE AND HEAT INPUT CURVES AT THE ORIGIN OF RIFLING

3"/70 TYPE E MOD O GUN

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diffusivity were assumed constant in these calculations. The paragraph Thermal Conductivity and Diffusivity below contains a discussion of the effects of temperature on these properties and the resulting effects on the heat transfer calculations. It is interesting to note that over one-half of the total heat input occurs during the first two milliseconds after projectile passage for both types of powders.

40mm Mark A Mod 1 Gun:

The bore surface temperature-time curves and the calculated heat transfer curves are shown in Figure 2. Each of these temperature-time curves represents the average of three rounds. The variation in the recorded temperatures for each set of three rounds with each type of propellant was not more than 10°C. These rounds are representative of the 15 rounds fired in this test, excluding the warming rounds. Four of the six original temperature oscillograms are reproduced in Figure 3. Note the extremely rapid response of the thermocouple at the instant of projectile passage on the solid propellant rounds, Figure 3. During the firing of the liquid propellant rounds, some temperature rise was indicated by the thermocouple prior to projectile passage. This is attributed to leakage of propellant past the sealing band of the projectile causing combustion in front of the projectile. (Pressure gauges installed at this location showed a rise in pressure prior to projectile passage also.) This temperature rise prior to projectile passage was neglected in the calculations of heat transfer on the liquid propellant rounds.

The total heat inputs at the instant of projectile exit from the barrel are 6.2 cal./sq.cm. and 5.1 cal./sq.cm. for the solid and liquid propellant rounds respectively. Because of the different muzzle velocities, the projectile exit times were slightly different for the two types of propellants as noted on the curves in Figure 2. Over one-half the total heat input occurs during the first 0.5 millisecond after projectile passage for both types of propellants.

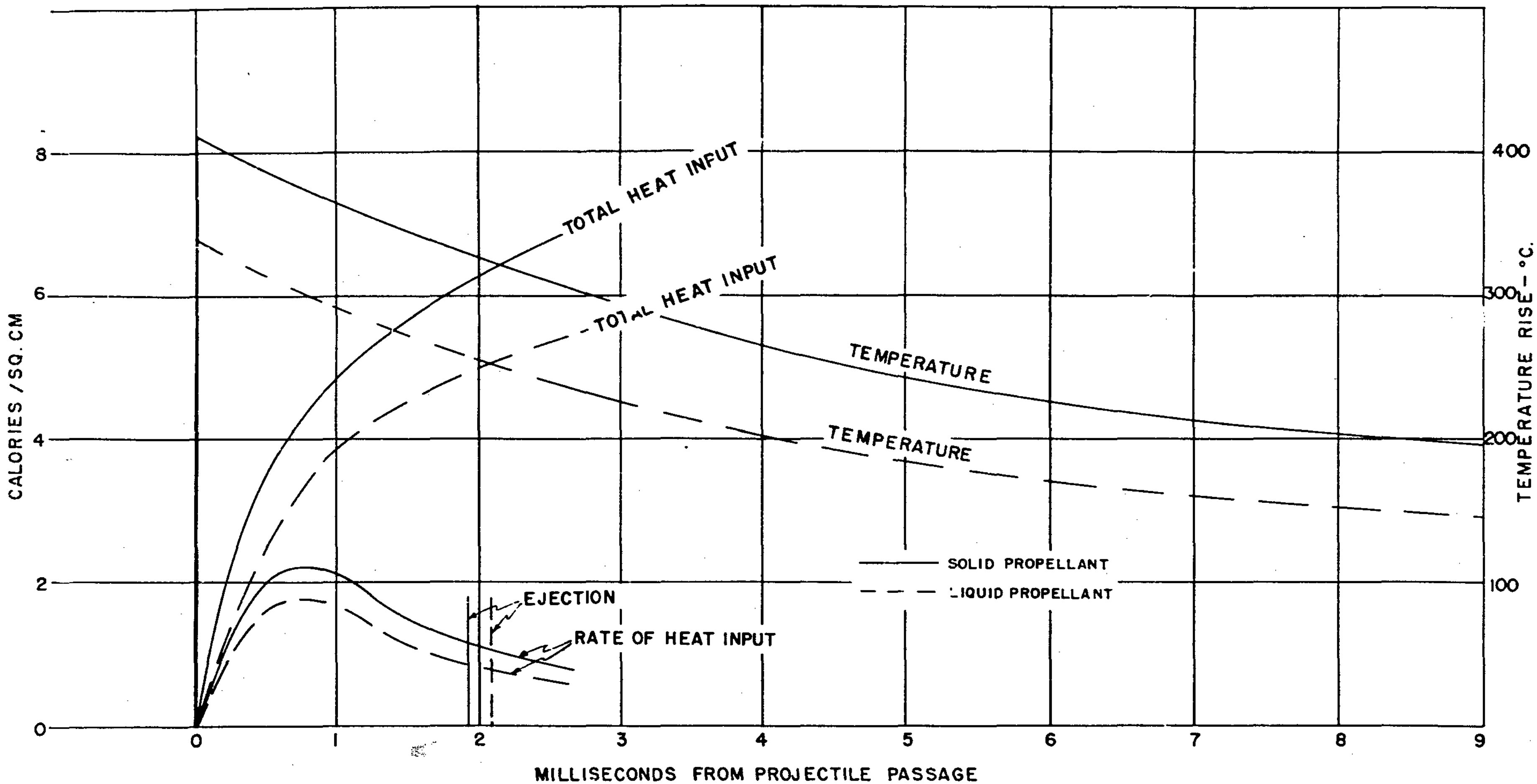

FIGURE 2

BORE TEMPERATURE AND HEAT INPUT CURVES AT 30".0 FROM THE BREECH FACE

40MM MARK A MOD I GUN

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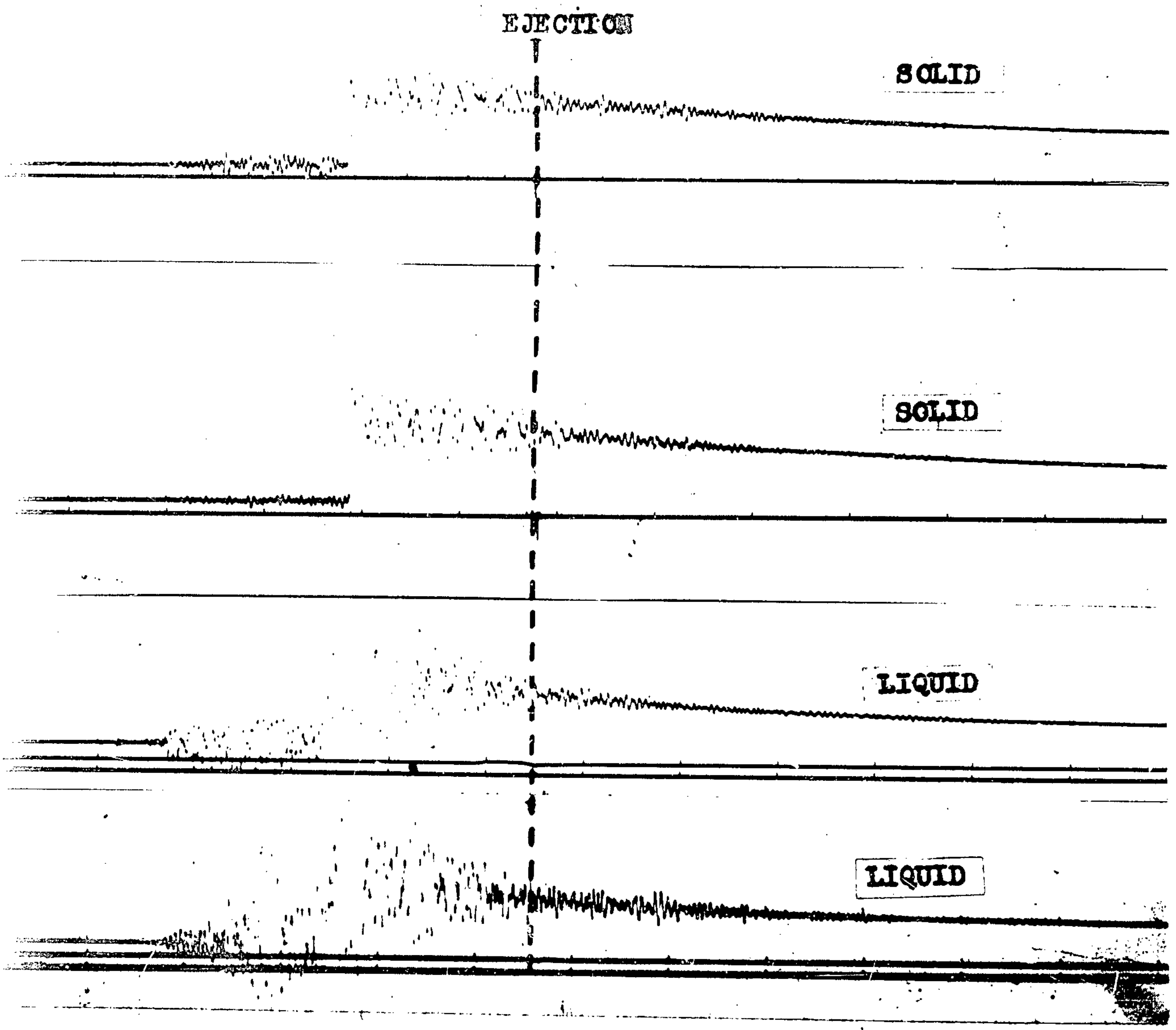

Timing Marks: 1000 cps
Location of Thermocouple: 30V0 from Breech Face
September 1954

BORE SURFACE TEMPERATURE
OSCILLOGRAMS

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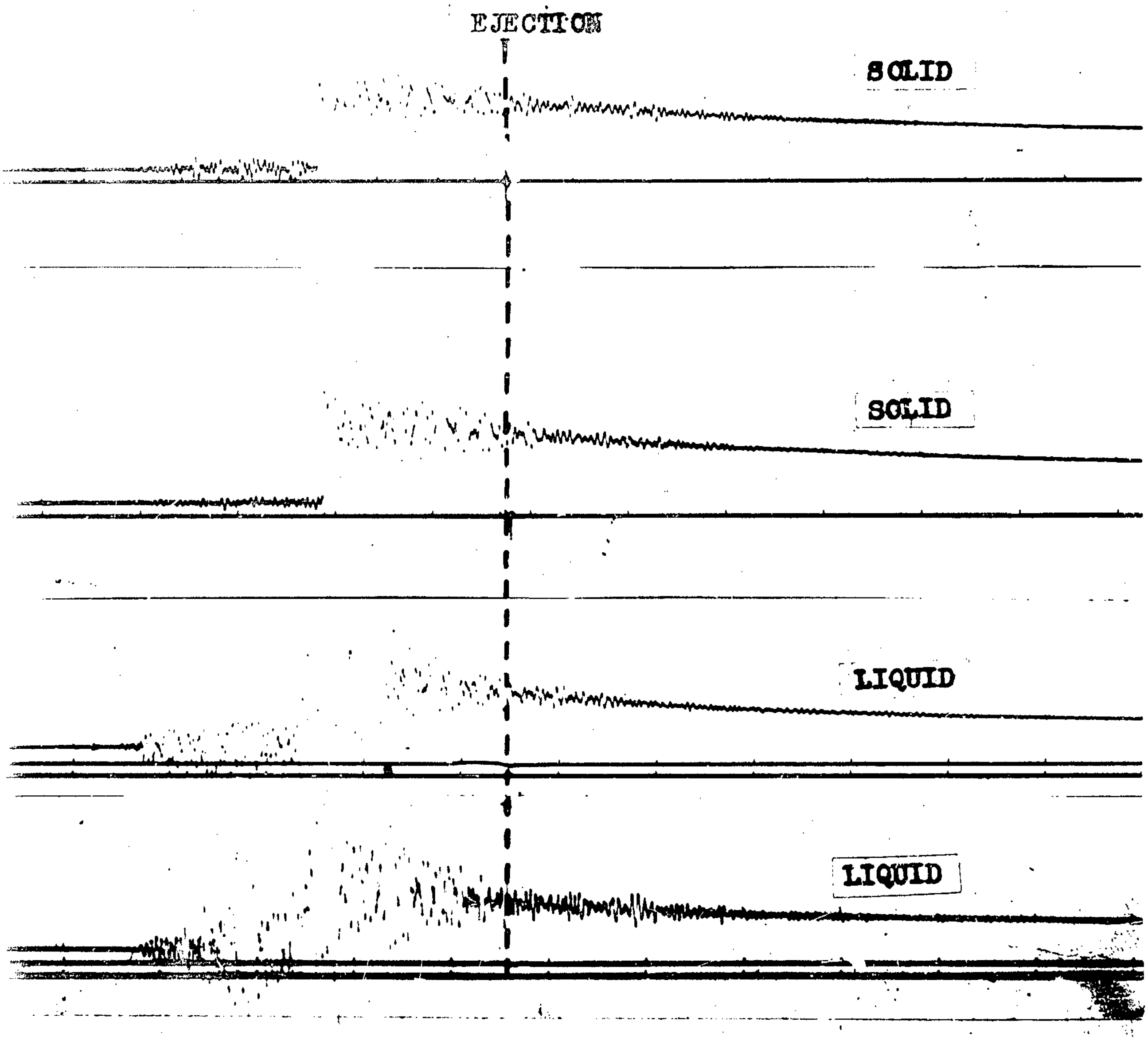
40MM Mark A Mod 1 Gun

Figure 3



Timing Marks: 1000 cps
Location of Thermocouple: 30V0 from Breech Face
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40MM Mark A Mod 1 Gun

Figure 3

Thermal Conductivity and Diffusivity:

The values for thermal conductivity and diffusivity used for the calculations in this report were 0.11 cal./sec.cm.^{2} °C/cm. and 0.096 cm.^{2}/sec. respectively. It was assumed that both of these properties were independent of temperature to simplify the calculations. Tests have been conducted in England and this country which show that these properties decrease in value by about 30% for steels in the temperature range above 800°C. Using these figures, the heat transfer values would be reduced by about 15%. Since the bore surface temperature curve for the "hot" powder used in the 3"/70 gun was well above 800°C during the time interval to projectile exit, the total heat input would be 26 cal./sq.cm. using these values. Also, since the bore surface temperature curve for the "cool" 3"/70 powder was about 800°C or higher for most of the time interval to projectile exit, the same values for these properties may be used with little loss in accuracy. This would then yield a total heat input of 21 cal./sq.cm. for the "cool" powder. These values for the total heat inputs for these two powders are very closely proportional to their respective calculated flame temperatures.

The bore surface temperatures recorded on the 40mm gun were relatively low and the heat transfer data would not change appreciably with the slight changes in the thermal properties over this temperature range.

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(b) NPG Conf Report No. 1130 "A Thermocouple to Record Transient Temperatures at the Bore Surface of Guns" of 15 July 1953
(c) NPG Conf Report No. 1296 "Bore Surface Temperatures in the 3"/70 Type E Mod 0 Gun Using Hot and Cool Powders" of 4 October 1954
(d) "Mathematical Theory of the Conduction of Heat in Solids" by H. S. Carslaw, 1945

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